Bone is Tough Where it Matters

5-Fold Greater Fracture Resistance for Short Cracks Across vs. Along Length

MSD Faculty Scientist Robert Ritchie and Staff Scientist Joel Ager, working with post-doctoral researcher Kurt Koester, have discovered that the true toughness of human bone is far greater than had been previously thought. Further, they found that for cracks shorter than one millimeter, the force required to drive them through bone is more than five times greater in the transverse direction across the bone, than in the longitudinal direction along its length. The work demonstrates not only that bone has evolved to be more difficult to break than to split, but also that it has a structure optimized to resist the propagation of cracks (extension of a preexisting crack) of physiologically relevant sizes.

Cortical (or compact) bone comprises the thin, hard outer shell of the long bones in the body; it is, for example, 3-5 mm thick at the mid-shaft of the 25 mm diameter humerus. High toughness–a material's ability to resist crack propagation is obviously desirable here and the toughness of bone has been measured numerous times over the last few decades. Most of these studies have measured the "initiation" toughness–that which is required to start a crack–and have converged on a value of 2-7 MPa√m, which is comparable to that of brittle ceramics such as alumina. This correspondence is surprising given that the microstructure of bone is considerably more complex than that of engineering ceramics. Prior work by Ritchie, for example, has shown that bone's microstructure has evolved to resist crack propagation over a range of length scales, by creating "crack bridging," which increases toughness with crack length. This contradiction can be explained because most prior studies had examined the toughness in human bone for initiation rather than propagation of cracks.

To study crack propagation with high spatial resolution, fracture tests on human bone samples were performed *in-situ* in an environmental scanning electron microscope (ESEM) capable of studying "normal" hydrated samples. The driving force required to both initiate and propagate cracks was measured to construct "crack-resistance curves" for both transverse and longitudinal orientations. The investigators found that, for sub-mm cracks, the fracture toughness values for transverse cracks could reach up to 25 MPa√m after 0.5 mm of crack propagation; several times higher than previously thought. Movies constructed from the ESEM images showed how such extraordinary crack-growth resistance is achieved, specifically via processes of crack deflection. As shown in the figure, rather than following a straight path across the bone, a growing transverse crack zigzags, requiring far more force to drive it forward. The crack deflection was further revealed in *ex-situ* 3-D imaging performed using the tomography beamline at the Advanced Light Source.

This work not only shows that the true transverse toughness of cortical bone is far higher than previously reported; it also reveals the mechanisms that evolution has produced to create tough composite materials. Future work will target the effects of aging and other factors on cortical bone toughness.

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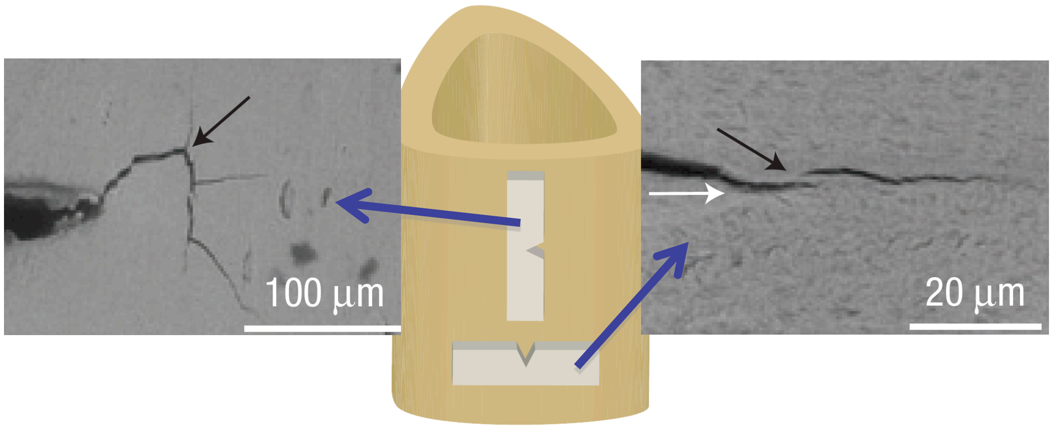
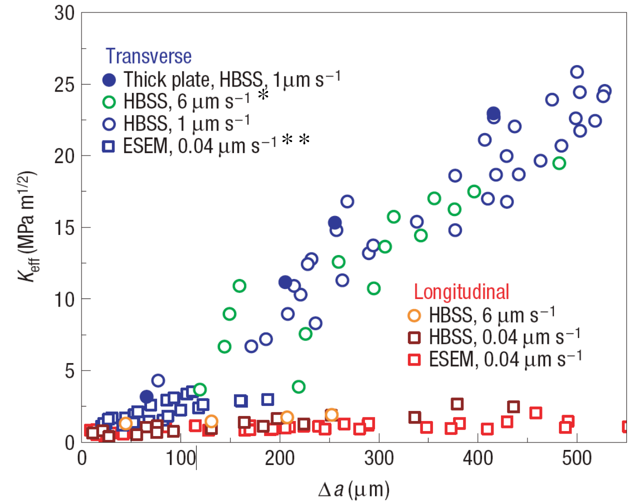


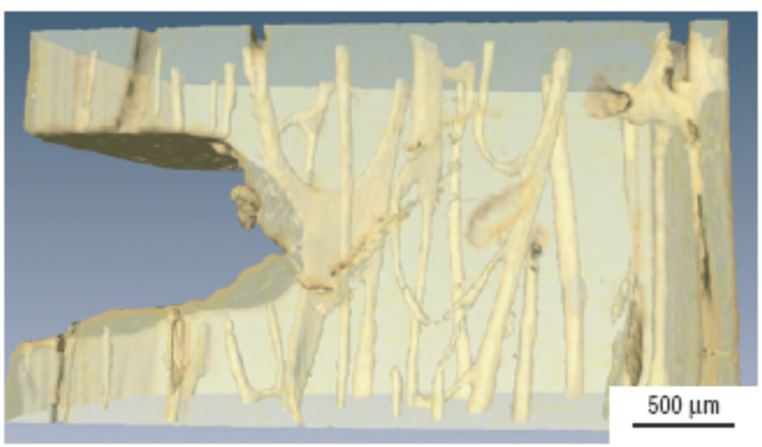


Images of cracks propagating in the transverse (left) and longitudinal (right) orientations in human bone. The images were obtained in an environmental scanning electron microscope. The black arrows indicate a crack deflection (left) and a bridge (right). The samples were obtained from the humerus bone broken in the orientations shown in the center.

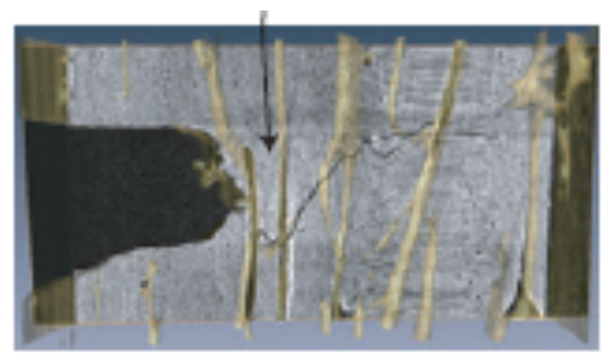
For short cracks, the fracture resistance (y-axis) increases with crack length and, for the transverse orientation (blue, green) reaches values of over 25 MPa $m^{-1/2}$ for 500 micron length cracks. This is several times larger than previously accepted values for the toughness of human bone. Far less fracture resistance is shown in the longitudinal orientation (red).

** HBSS—Hanks' balanced salt solutions*

***ESEM—Environmental scanning electron microscope*



"Slices" through 3-D images obtained by x-ray tomography reveal that deflections (arrow, right) occur at the Haversian canals (vertical features, left) which run along the long axis of cortical bone. This aspect of bone's microstructure makes a crucial contribution to its toughness.



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